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MOUNTAIN PINE BEETLE DAMAGE AND CONTAGION MODELING: SOME CONCEPTS AND APPROACHES

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MOUNTAIN PINE BEETLE DAMAGE AND CONTAGION MODELING: SOME CONCEPTS AND APPROACHES

by

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ABSTRACT

This paper describes various concepts and approaches relative to modeling mountain pine beetle (MPB) contagion effects within and among forest stands for use as a component of Integrated Pest Impact Assessment System (IPIAS). This information was developed at a workshop held June 25-29, 1984, in Breckenridge, Colorado (Hamilton et al. 1984)[3/]. The workshop participants focused on two critical aspects: 1) a mountain pine beetle damage model, and 2) the dynamics of a contagion model.

In developing a mountain pine beetle damage model, participants avoided the usual population dynamics approach. The advantage of not having an explicit representation of mountain pine beetle numbers is the avoidance of many nonquantified relationships that would otherwise be required. The primary calculations in the mountain pine beetle model will include: 1) hazard indices based on stand characteristics; 2) trees killed; 3) an MPB brood production index; 4) the probability of an outbreak starting or growing; and 5) an updated MPB index based on current year brood production and dispersal.

The contagion model will calculate how the beetles, and related tree mortality, will spread to surrounding stands. Several different approaches to representing this phenomenon were discussed. A modification of a dispersal matrix (grid cell) approach previously used to model dispersal of spruce budworm was proposed as a starting point.

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The results of this workshop will come to fruition through an Intra-Agency Agreement (IAG-RM-84-73) "Development of Pest, Stand and Contagion Models and Integration Into a Geographic Information System", with Intermountain Forest and Range Experiment Station; Principal Investigator, Albert R. Stage.

INTRODUCTION

The USDA Forest Service is committed to the concept of Integrated Pest Management (IPM). While IPM has many definitions, most contain two basic thoughts: A decision process that considers both ecological and economic criteria, and the availability of one or more management tactics to effectively deal with pest problems. Pest management decisions must be based on how pest activity impacts resource management objectives. In management of forest lands, particularly those in the public sector, resource management objectives can be highly variable and often conflicting. This greatly increases the complexity of making pest impact assessments.

Traditionally, the value of trees as a timber resource has often been the only impact readily quantifiable for economic analysis. This is because the effects of forest pests, such as tree mortality and growth loss, are easily measured with relative ease and lend themselves to marketplace evaluation.

Pest related social and economic impacts, such as aesthetic and recreational values, are difficult to estimate because they primarily involve personal attitudes not directly subject to marketplace evaluation. These considerations are not within the traditional realm of forestry or forest pest management and the need to involve people from other scientific disciplines, including economists and sociologists, is essential.

There are three areas where sound impact assessments are vital in forest pest management decisionmaking. First and foremost, they are needed to fully integrate pest management considerations early in the forest planning process when the full range of options is avilable to the resource manager. We must also keep in mind, however, that in the foreseeable future, much of our forest land base will continue to exist as wild, unmanaged stands highly susceptible to periodic episodes of catastrophic outbreaks. Second, sound data on the impacts of these outbreaks are required for land managers to make on-the-ground decisions for appropriate treatment tactics. Lastly, State and Federal program managers need impact information to secure adequate funding for large scale treatment efforts.

WORKSHOP OBJECTIVES

In recent years, USDA Forest Service, Forest Pest Management personnel have been involved in developing methods for assessing impacts of forest pests. The result of much of this work is the Integrated Pest Impact Assessment System (IPIAS) (Daniel et al. 1983). This system combines features of the

U.S. Fish and Wildlife Service's geographic information system (MOSS); a set of models representing mountain pine beetle (MPB) dynamics, forest stand growth and yield, and socioeconomic impacts; and a System 2000 forest data base.

At a February 13-18, 1983 IPIAS review workshop (Anonymous 1983), forest resource managers identified several refinements which they felt would make IPIAS more useable in the field. These refinements included addition of a contagion component to the mountain pine beetle model, improvement to or replacement of the existing mountain pine beetle model, better integration of the pest and forest stand models, and better integration of the biological and forest models with the geographic information system.

In order to specify the technical nature of the mountain pine beetle and contagion models and how they would interact with the other system components, the USDA Forest Service, Forest Pest Management/Methods Application Group sponsored a workshop June 25-29, 1984, in Breckenridge, Colorado. Specific objectives of the workshop included:

(1) review the IPIAS system and the general refinements suggested at the February 1983 workshop (Anonymous 1983);

(2) discuss alternative mountain pine beetle damage and contagion modeling approaches;

(3) determine the damage and contagion modeling approaches to be implemented in IPIAS;

(4) discuss implications of these approaches for other IPIAS components; and

(5) discuss data and methods needed to calibrate and verify IPIAS output.

SYSTEM ARCHITECTURE

The general architecture of IPIAS is presented in Figure 1. The System 2000 (S2K) data base provides information on existing stand conditions. A set of simulation models then predicts alternative forest conditions resulting from specific treatments, pest damage, or normal growth and mortality. These alternative residual stand conditions are also stored in the data base. The data base management and geographic information systems produce tabular reports and maps of output variables of interest to various forest planners and staff specialists (wildlife, recreation, timber management, and economics). This general architecture was developed through a series of previous workshops.

Resource management issues, such as forest pest management, involve complex interactions among a variety of economic, social, and environmental factors. While some individual components of such a resource system may be well

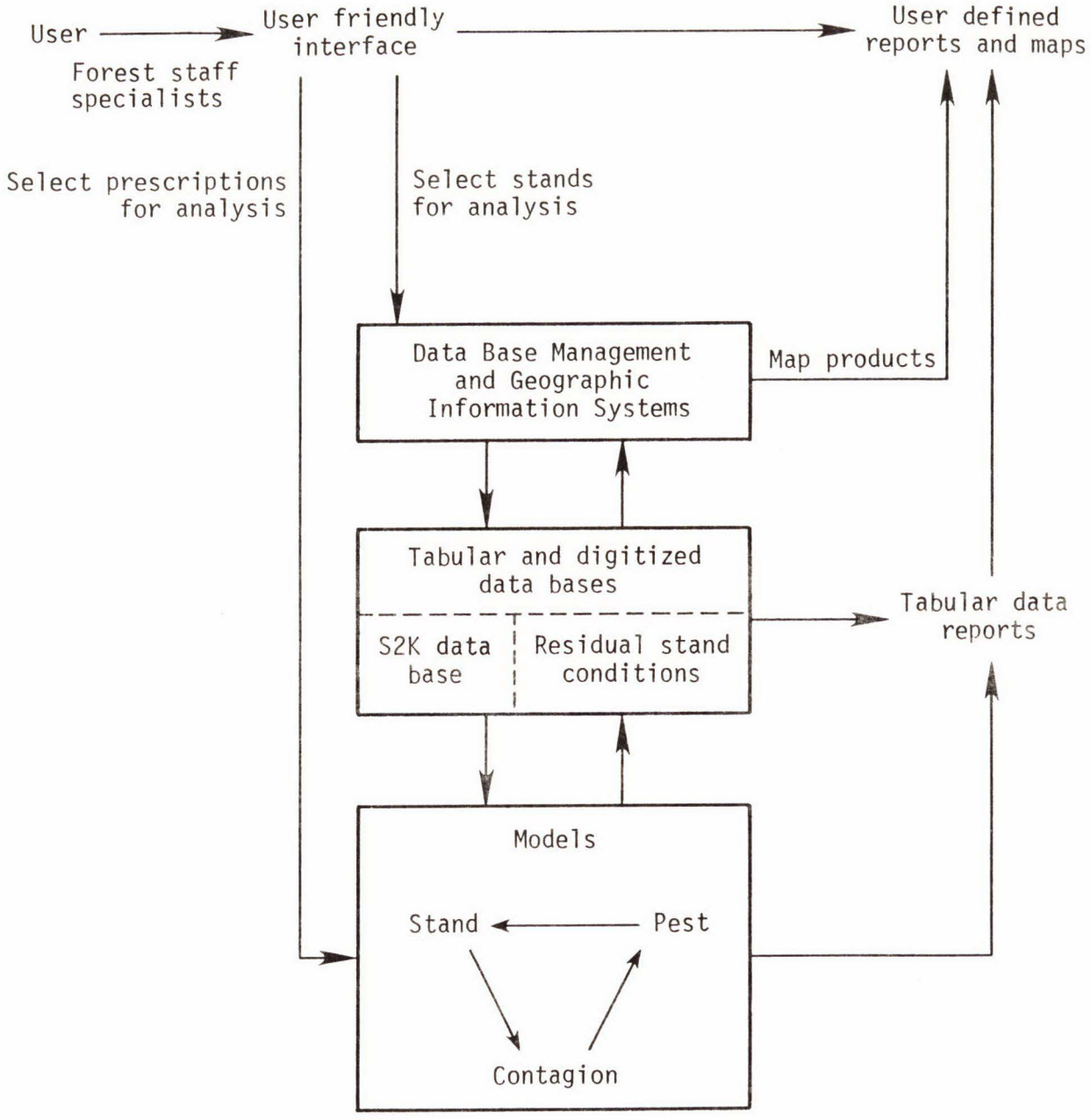

Figure 1. General architecture of IPIAS.

understood, the complexity of component interactions generally results in poor understanding of the system as a whole. The representation of the resource system used in an analysis must be sufficiently detailed and flexible to be realistic and address major management concerns adequately, yet must remain simple enough to be understandable and useable. In addition, the system must complement or enhance existing planning processes and be compatible with existing computer hardware or it might fail institutionally.

Early in the design phase of model development, a major effort is required to define the key elements of the managed system which must be modeled to capture its essential behavior in both time and space and meet the above criteria of detail and understanding. This process was initiated for the mountain pine beetle damage and contagion models by having workshop participants identify management alternatives (actions) the system should include, output variables (indicators) the system should produce to allow evaluation of the various effects of these actions, and the proper spatial and temporal resolution for the models. Participants also discussed the planning and management environment in which IPIAS will be used and the operating environment in which it will be implemented. Throughout the workshop, the interfaces among models were discussed and refined.

USER INFORMATION NEEDS - The management actions that IPIAS should be able to evaluate and the outputs or indicators the system should produce for forest staff specialists are presented in Tables 1 and 2. For purposes of this report, they are organized into the levels of spatial resolution subsequently identified. These actions and indicators represent the participants initial specification of the simulation models.

SPATIAL AND TEMPORAL RESOLUTION - Spatial resolution is the geographic area to be covered by the models, as well as the degree to which that area needs to be subdivided into smaller units in order to represent the dynamics of the processes involved. Three levels of spatial resolution were defined. Level 0 is the lowest level with a geographical reference. While Level 0 units would most likely correspond to forest stands, they could represent somewhat larger units such as a forest type or cells in a grid system. Level 0 units will generally be referred to as stands in the remainder of this report. Level 1 is a contiguous aggregation of Level 0 units in a topographic (e.g., a watershed) or management (e.g., a compartment, an entomological unit) context. IPIAS will represent mountain pine beetle contagion among Level 0 units within a Level 1 unit. Level 2 represents an entire forest composed of Level 1 units. IPIAS will not model contagion among Level 1 units within the forest nor is it likely to be feasible to run IPIAS on all Level 1 units independently. At Level 2, risk or hazard maps could be generated, based on IPIAS output, from representative Level 1 units.

Temporal resolution refers to the basic time-step of model calculations and the number of iterations needed to cover the time horizon of interest. IPIAS should be capable of representing time horizons from 5 to 200 years. The shorter time frame would be used to analyze short-term management decisions concerning specific pest outbreaks. The longer time frame, which corresponds to the maximum age of a lodgepole pine stand, would be used to address

Table 1. Management actions to be included in IPIAS simulation models.

Spatial level	Action
Level . - lowest level that has a geographical reference (e.g., a forest stand).	1) Control stand density - thin from below - thin from above - special selection thinning (e.g., based on size, species, pest/pathogen)
	2) Regeneration method - clear cut - seed tree - shelter wood - selection - planting - seeding - site preparation " burning " mechanical
	3) Fertilization
	4) Actions against mountain pine beetle - chemical treatment on trees " infested trees " noninfested trees - pheromones " baiting " confusion - destruction of infested trees " cut, pile, and burn " burn standing " detonation " debark
Level 1 - contiguous aggregation of Level units in some context such as topography or entomological unit.	1) Artificial spread of beetles
	2) Control harvest pattern - size and spatial distribution
	3) Control access
	4) Sanitation
	5) Schedule harvest
	6) Control burn

Table 2. Output variables to be provided by IPIAS simulation models.

Spatial level	Output variable
Level Ø - lowest level that has a geographical reference (e.g., a forest stand).	1) Yield
	2) Diameter distribution by species - for host trees, distribution also by dead, infested, noninfested
	3) Insect indicators - e.g., # beetles/ sq. ft. of bark surface
	4) Treatment cost
	5) Radial growth increment
	6) Mountain pine beetle risk and susceptibility indicators - e.g., - probability of independent outbreak - probability of outbreak given surrounding conditions - rate of damage accretion given an outbreak
	7) Fuel load
	8) Shrub and cover - links for recreation, wildlife, and socio-economic analyses
Level 1 - contiguous aggregation of Level Ø units in some context such as topography or entomological unit.	1) Proportion of Level Ø units exceeding a critical threshold - e.g., # of red-top clusters
	2) Yield
	3) Proportion of Level Ø units in various stages of stand development
	4) Proportion of Level Ø units (and pattern) in various hazard rating levels
	5) Proportion of units having access

long-term planning needs. An annual time-step would normally be used for model calculations; a 5- or 10-year increment might be used when forest conditions are changing slowly or when there are no pest outbreaks to track. Likewise, IPIAS could produce outputs annually or every 5 to 10 years, depending on forest conditions.

COMPONENT INTERFACES - Interfaces among simulation models within IPIAS were developed by constructing an interaction matrix (Figure 2). For each column of the matrix (i.e., for each model), participants were asked what information had to be provided by the other models (row elements within that column) in order for their model to represent the consequences of various management actions. This matrix and associated discussions not only specified further the structure of the model section of IPIAS but also helped identify data and analyses associated with these information transfers that must be developed before IPIAS can be used.

The interaction matrix was modified throughout the workshop as the modeling approaches for mountain pine beetle and contagion were developed. The matrix in Figure 2 has been edited to reflect the information transfer required by the modeling approaches ultimately chosen.

MOUNTAIN PINE BEETLE DAMAGE MODEL

OVERVIEW - Workshop participants concluded that a mountain pine beetle population dynamics model was not required to represent results of the management actions in Table 1. Therefore, a simpler model was developed that will track an index of potential mountain pine beetle damage (subsequently referred to as the MPB index). The primary output from this model will be actual tree mortality (red-top trees) which will be computed from the MPB index and the hazard rating for each stand. The advantages of this approach include the avoidance of many nonquantified relationships that would be required for a population dynamics model and a readily available source of input and verification data (sketch maps of red-top clusters). Although mountain pine beetle population dynamics will not be explicitly represented, currently available population data will be used for setting limits for this model.

Clusters of red-top trees are often used as an initial indicator of a mountain pine beetle outbreak. Clustering of red-top trees will not be modeled explicitly; the initiation or continuation of an outbreak will be modeled as a function of beetle and hazard indices for each Level 0 unit. As a result, the stand model for IPIAS will not have to keep track of spatial coordinates of all trees in a Level 0 unit. Other stand indicator variables (e.g., the number of green infested trees) will be modeled as functions of the number of red-top trees and other Level 0 unit attributes. Management actions will be incorporated either in the Level 0 stand model or as weighting factors on parameters in the mountain pine beetle damage model.

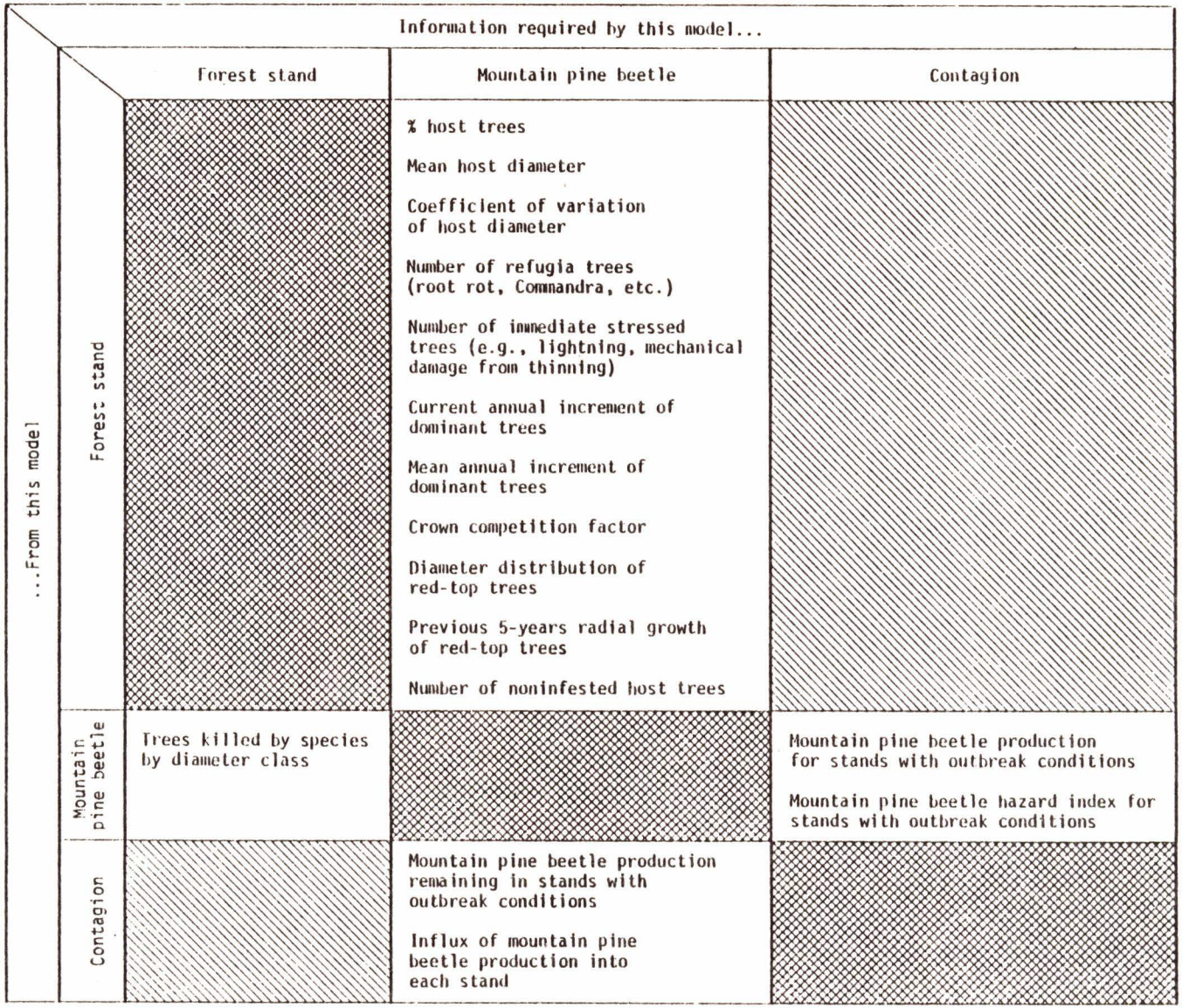
Information required by this model...
...From this model
Forest stand
Mountain pine beetle
Contagion
% host trees
Mean host diameter
Coefficient of variation of host diameter
Number of refugia trees (root rot, Commandra, etc.)
Number of immediate stressed trees (e.g., lightning, mechanical damage from thinning)
Current annual increment of dominant trees
Mean annual increment of dominant trees
Crown competition factor
Diameter distribution of red-top trees
Previous 5-years radial growth of red-top trees
Number of noninfested host trees
Trees killed by species by diameter class
Mountain pine beetle production for stands with outbreak conditions
Mountain pine beetle hazard index for stands with outbreak conditions
Mountain pine beetle production remaining in stands with outbreak conditions
Influx of mountain pine beetle production into each stand

Figure 2. Interaction matrix for IPIAS simulation models.

APPROACH - The calculation sequence for the MPB damage and contagion models is presented in Figure 3. The primary calculations in the MPB model will include: (1) stand hazard indices based on stand characteristics; (2) trees killed; (3) MPB brood production (expressed in the same units as the MPB index); (4) the probability of an outbreak starting or growing; and (5) the updated beetle index based on this year's brood production and dispersal.

Stand Hazard Index - Stand hazard indices (Figure 3,a) will be needed for subsequent calculations of basal area killed, brood production, and probability of an outbreak starting or growing. The contagion model will also need a hazard index to calculate infestation of trees by dispersing beetles. Although these various hazard indices will be based on similar variables, the functional combination of variables may be different for each index. Variables to be used in calculating stand hazard indices include:

(1) refugia trees - i.e., trees with root rots, rusts, other beetles, etc., which do not produce large numbers of beetles, but help maintain low level populations;

(2) weather - primarily drought, late season temperature;

(3) time since physiological maturity - defined as intersection of current and mean annual increment curves for dominant trees;

(4) immediate stressed trees - i.e., damaged due to lightning strikes, thinning operations, girdling, etc.;

(5) mean host tree diameter and coefficient of variation of host diameter;

(6) percent host trees;

(7) crown competition factor;

(8) elevation; and

(9) latitude.

Trees Killed - Determining which trees in a stand are killed (Figure 3,b) will require two operations. Assuming trees of average vigor, a potential basal area killed will first be calculated as a function of both the mountain pine beetle index, calculated at the end of the previous year, and a stand hazard index as described above. The tree list for the stand will then be sorted by size. Larger trees are generally more prone to infestation than smaller ones, so the largest host tree in the stand will be killed first. Since the amount of beetle damage required to kill a tree depends on the tree's vigor (e.g., as indicated by current growth, crown ratio), the potential basal area killed will then be reduced by an amount based on that tree's actual basal area modified by a vigor factor. Thus, the same potential basal area killed will result in only a few trees actually killed in a healthy

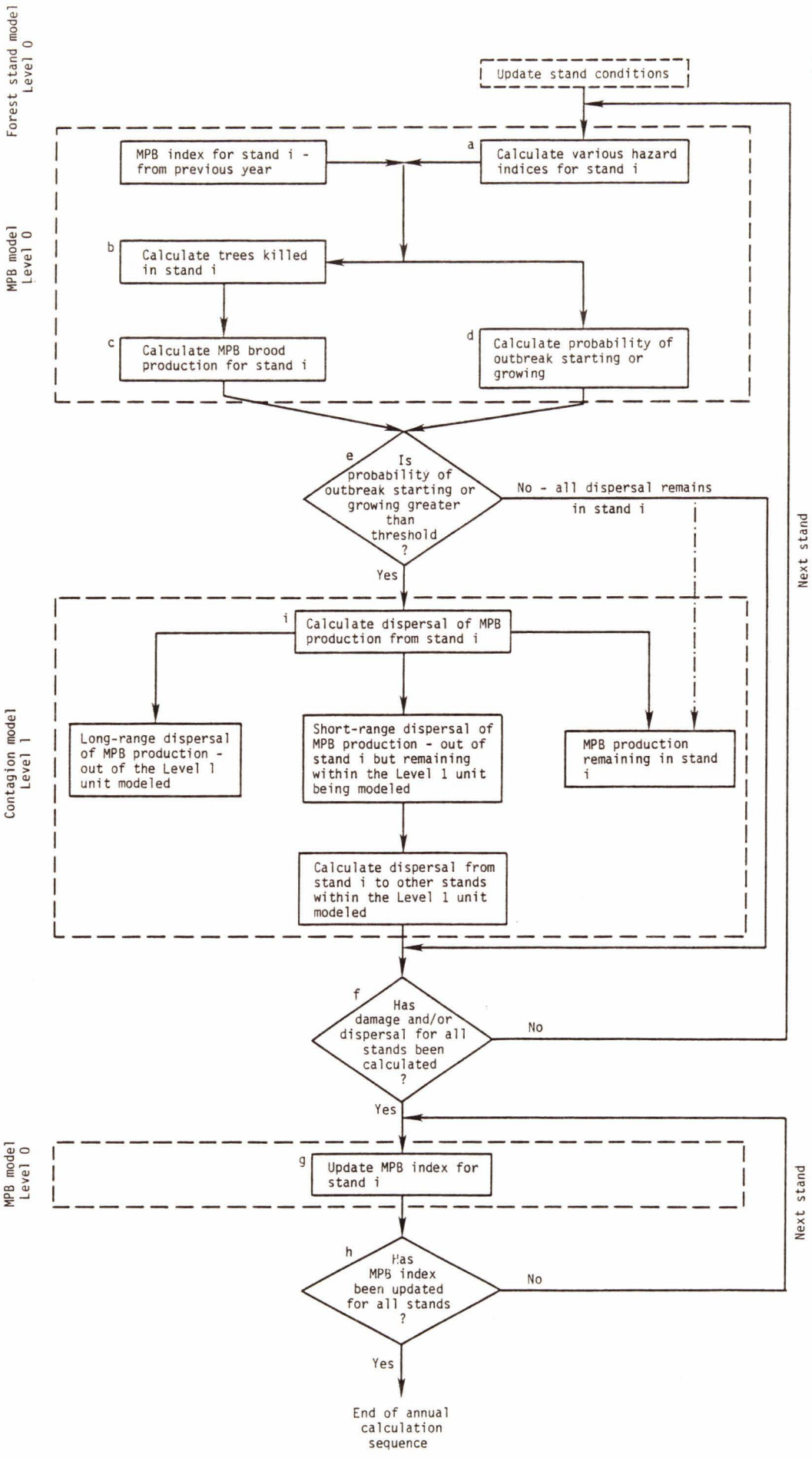
Forest stand model Level 0
Update stand conditions
MPB model Level 0
MPB index for stand i - from previous year
a
Calculate various hazard indices for stand i
b
Calculate trees killed in stand i
c
Calculate MPB brood production for stand i
d
Calculate probability of outbreak starting or growing
e
Is probability of outbreak starting or growing greater than threshold ?
No - all dispersal remains in stand i
Yes
Next stand
Contagion model Level 1
i
Calculate dispersal of MPB production from stand i
Long-range dispersal of MPB production - out of the Level 1 unit modeled
Short-range dispersal of MPB production - out of stand i but remaining within the Level 1 unit being modeled
MPB production remaining in stand i
Calculate dispersal from stand i to other stands within the Level 1 unit modeled
f
Has damage and/or dispersal for all stands been calculated ?
No
Yes
MPB model Level 0
g
Update MPB index for stand i
Next stand
h
Has MPB index been updated for all stands ?
No
Yes
End of annual calculation sequence

Figure 3. Calculation sequence for mountain pine beetle damage and contagion models.

stand but a larger number killed in a stressed stand. The next largest host tree will then be evaluated and the process continued until the potential basal area killed has been reduced to zero or all host trees in the stand are killed.

Brood Production - Brood production (Figure 3,c) will be expressed in the same units as the MPB index. It will be calculated as a function of:

(1) the mountain pine beetle index;

(2) a stand hazard index as described above;

(3) the diameter distribution of green infested trees in the current year; and

(4) weather.

The primary weather factor to be considered will be the occurrence of a cool fall followed by an abrupt temperature drop in early winter. Such conditions reduce mountain pine beetle production. Droughts can decrease the resistance of trees, which results in increased brood production, but this factor is already included in the hazard index.

Probability of Outbreak Starting or Growing - The probability of a mountain pine beetle outbreak starting or growing in a stand (Figure 3,d) will be a function of the MPB index for the stand and a stand hazard index as described above. An approach that might be used involves representing this function by a surface (Figure 4) composed of two logistic functions, one for the beetle index and one for the stand hazard index (Paine et al. 1984):

$$f(B_i, H_i) = 1/[(1 + e^{a + bB_i})(1 + e^{a' + b'H_i})]$$

where $f(B_i,H_i)$ = the probability of an outbreak starting or growing in stand i

B_i = the MPB index for stand i

H_i = a hazard index for stand i

$e = 2.71828$

a,b,a',b' = model coefficients.

In Paine, et al. (1984), the beetle index is a function of the rating values for the population, the compartment, and the region; the stand hazard index is a function of basal area, height, and landform. There was some debate at the workshop as to whether separate functions should be used for the start and for the continuation or growth of an outbreak or whether different

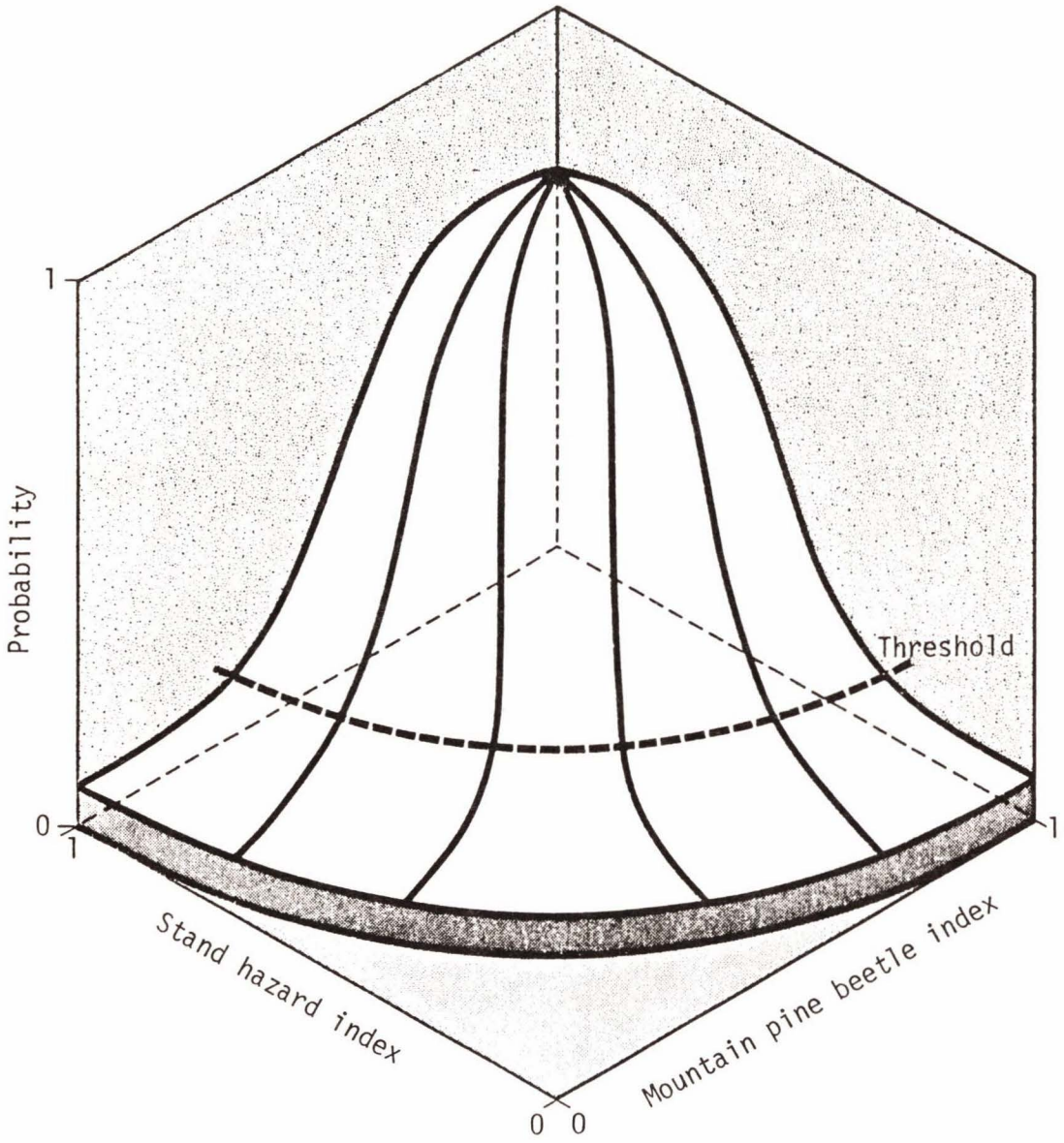

Figure 4. Surface representing the probability of a mountain pine beetle outbreak starting or growing (modified from Paine et al. 1984).

thresholds on the same surface would be adequate. This will be evaluated as the model is developed. Even if the hazard and MPB indices are below the threshold, the model will produce some "random" outbreaks in stands based on user specified assumptions about infestation levels in nearby Level 1 units.

If an outbreak begins or continues in a stand (Figure 3,e), then dispersal of brood production out of that stand will be calculated next by the contagion model.

Mountain Pine Beetle Index - After mountain pine beetle dispersal has been calculated for all stands with outbreak conditions (Figure 3,f), a new MPB index will be calculated (Figure 3,g) based on the index of beetles remaining within the stand and the index of influx from other stands. In addition, the mountain pine beetle index will be a function of the diameter distribution of red-top trees from the previous year and the radial growth of those red-top trees the previous five years. The radial growth information will be used to calculate phloem thickness.

After the MPB index for all stands has been calculated (Figure 3,h), a new sequence of annual calculations will be performed. This iterative process will be continued until the time horizon of interest has been simulated.

CONTAGION MODEL

OVERVIEW - For each stand with mountain pine beetle outbreak conditions, the contagion model will calculate the influx of MPB index units for all surrounding stands to which beetles disperse. Several different approaches to representing this phenomenon were discussed at the workshop.

Dispersal Matrix Approach - The proportional dispersal of mountain pine beetles from a grid cell to all surrounding cells could be represented by an array whose elements depend upon factors such as topography and weather. For all stands in a Level 1 unit, this information would be stored in a matrix. This matrix would be used in conjunction with stand susceptibility characteristics to determine the actual influx index for each stand. This approach has been used previously to model dispersal of spruce budworm and larch casebearer (Long 1977, 1980a; Thomson 1979).

Dispersal Distance Approach - Another approach discussed would involve successively calculating potential dispersal distances from an outbreak center as

$$H_n = na\sqrt{r}$$

where H_n = radius of a circle within which all red-top trees are located at time n

n = generation time

a = mean dispersal distance

r = intrinsic rate of increase of beetle index.

If "a" is represented by a vector dependent on direction, noncircular dispersal could be simulated. The potential dispersal distance(s) would be modified by forest susceptibility conditions to determine actual dispersal distances. One drawback to this approach would be the geographic information processing required to develop a composite susceptibility index for a circular area covering parts of several forest stands. A similar problem would exist when beetle influx indices for the circular areas were composited to indices for each stand.

Surface Fitting Approach - The last approach discussed would involve a surface fitting approximation to a diffusion equation (Long 1980b). A coefficient vector of slope multipliers would be used to modify diffusion in different directions based on topography, weather, susceptibility, etc. The primary advantage of this approach would be the reduced amount of computer storage required; coefficients representing the surface would be stored rather than data for each regularly spaced grid cell. Disadvantages of this approach would include the requirement for regularly spaced grid cells and the inability to model "jumps" in dispersal (i.e., dispersal that is not a diffusion process).

APPROACH - The general contagion model suggested for IPIAS is a modification of the dispersal matrix approach. Calculations will be made for two types of beetle movement (initial dispersal from a stand with outbreak conditions to adjacent stands, and continued dispersal outward from these adjacent stands) and for infestation of green trees as the beetles move through stands. The sequence of calculations is presented in Figure 5 and described in more detail below.

Initial Dispersal - It is assumed that all beetles in a stand will disperse to some extent (Figure 5,i). Some of those beetles will remain within the stand while others will move to neighboring stands or be carried out of the Level 1 unit entirely. The proportion of mountain pine beetle production that remains within a stand will be calculated as a function of the number of available host trees and the size of the stand (perhaps in the direction of the prevailing wind). Long range dispersal (beetles carried out of the Level 1 unit) is primarily associated with strong winds along ridge tops. Therefore, the calculated proportion of beetle production lost to long range dispersal will increase as distance from the stand to a ridge top decreases. The remainder of the beetle units (i.e., not remaining in the stand or lost to long range dispersal) will disperse to nearby stands.

As an example, assume a mountain pine beetle outbreak in stand 12 in Figure 6 with an associated mountain pine beetle production of 2,000 units. Further, assume that due to the stand's condition and location, 20 percent of that

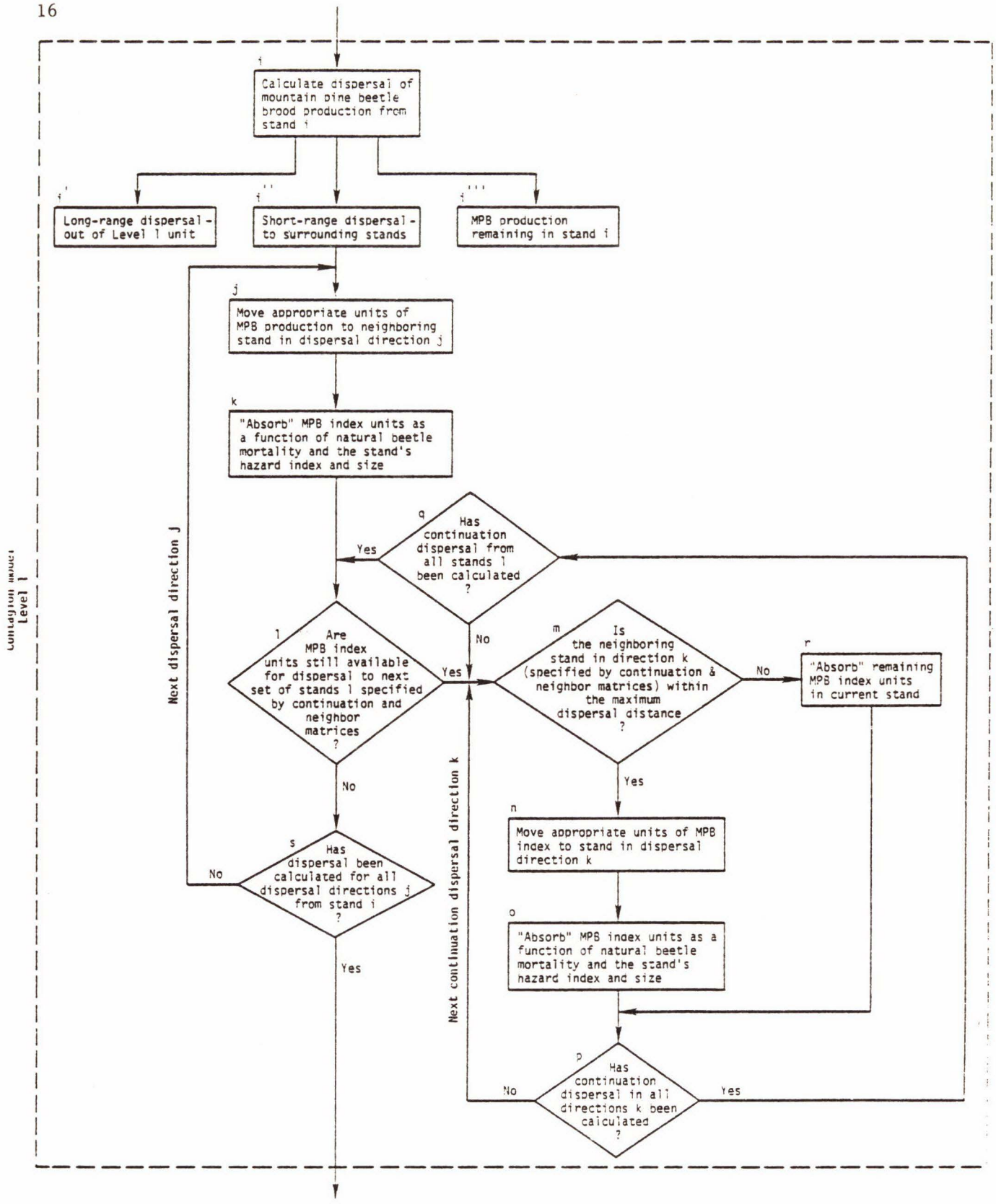
Contagion model Level 1
i
Calculate dispersal of mountain pine beetle brood production from stand i
i'
Long-range dispersal - out of Level 1 unit
i''
Short-range dispersal - to surrounding stands
i'''
MPB production remaining in stand i
j
Move appropriate units of MPB production to neighboring stand in dispersal direction j
k
"Absorb" MPB index units as a function of natural beetle mortality and the stand's hazard index and size
q
Has continuation dispersal from all stands l been calculated ?
Yes
No
l
Are MPB index units still available for dispersal to next set of stands l specified by continuation and neighbor matrices ?
Yes
No
m
Is the neighboring stand in direction k (specified by continuation & neighbor matrices) within the maximum dispersal distance ?
No
r
"Absorb" remaining MPB index units in current stand
Yes
n
Move appropriate units of MPB index to stand in dispersal direction k
o
"Absorb" MPB index units as a function of natural beetle mortality and the stand's hazard index and size
p
Has continuation dispersal in all directions k been calculated ?
No
Yes
Next continuation dispersal direction k
s
Has dispersal been calculated for all dispersal directions j from stand i ?
No
Yes
Next dispersal direction J

Figure 5. Calculation sequence for contagion model.

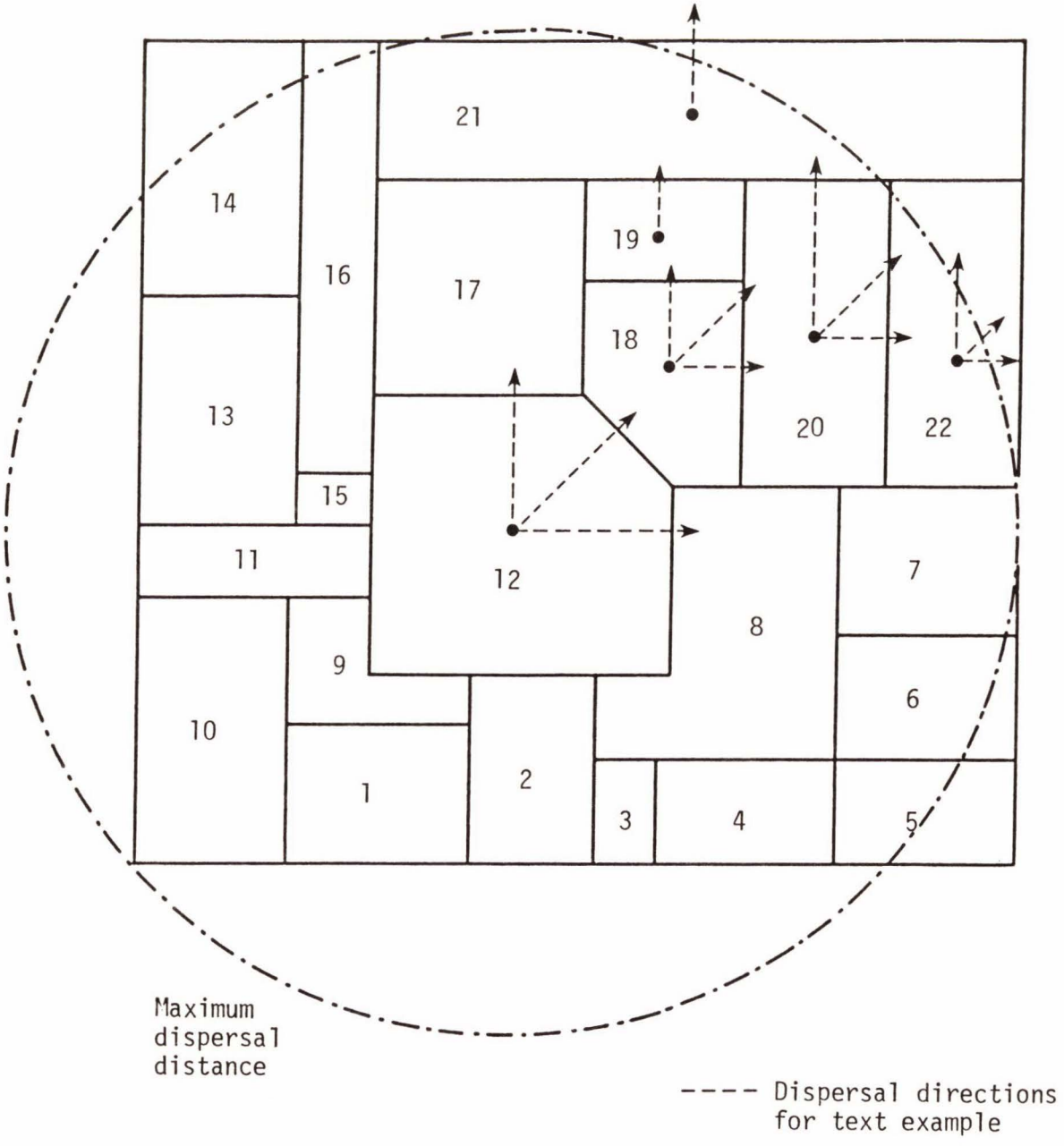

Figure 6. Forest stands in a representative Level 1 unit.

production will remain in the stand and 10 percent will be carried off by high winds along a nearby ridge top. Therefore, 1,400 beetle units will be left for short range dispersal.

Move MPB Index Units to Neighboring Stands - The short range dispersal of mountain pine beetles to neighboring stands (Figure 5,j) will be governed primarily by wind and topography. For each Level 1 unit, a wind rosette modified by dominant topography will be specified (Figure 7); the value for each spike of the rosette will be used as the proportion of beetles dispersing in that direction. The remainder of the contagion calculations will be performed iteratively for each dispersal direction specified in the rosette.

In the example, 560 (40 percent) of the 1,400 mountain pine beetle units dispersing from stand 12 will move in the first direction (to the northeast). A neighbors matrix (Table 3) will be used to determine the corresponding forest stand. Thus, row 12 of the neighbors matrix specifies that the 560 beetle units dispersing in direction 1 will end up in stand 18.

"Absorb" MPB Index Units - Some of the beetles that move into stand 18 will die while others will infest host trees (Figure 5,k). The "mortality" of beetle units will probably be a user-specified proportion (i.e., not calculated as a function of stand characteristics). The number of beetle units infesting green host trees will be determined as a function of a stand hazard index (described earlier) and the size of the stand. One approach discussed at the workshop would involve calculating the potential number of beetle units that would remain in the stand, based on its hazard index, then modifying that number, based on the width of the stand in the direction of dispersal or the overall shape of the stand. If the stand is relatively narrow in the direction of dispersal, or it is relatively regularly shaped, it would be assumed that beetles could disperse across the entire stand. Thus, all of the potential beetle units would infest trees. However, if the stand is relatively wide or is extremely elongated, then beetles may only be able to disperse across part of the stand, in which case the number of beetle units actually infesting trees would be less than the potential. If all of the beetle units moving into stand 18 from 12 either die or infest green trees, then dispersal calculations for the next direction from stand 12 will be performed. If there are excess beetle units remaining in stand 18, then continuation dispersal for the excess will be calculated (Figure 5,m-r).

For the example, assume that 10 percent of the 560 beetle units moving into stand 18 die and that 15 percent infest green trees because the stand has a relatively low hazard index. This leaves 420 units (0.75 x 560) to continue dispersing.

Continue Dispersal and Absorbtion of Excess MPB Units - If there are excess beetle units that continue to disperse (Figure 5,l), the subsequent dispersal directions of those units will be specified by a continuation matrix (Table 4). For each direction of initial influx, this matrix specifies the directions in which subsequent dispersal can occur. One reason for utilizing a continuation matrix for subsequent dispersal rather than the wind/topography

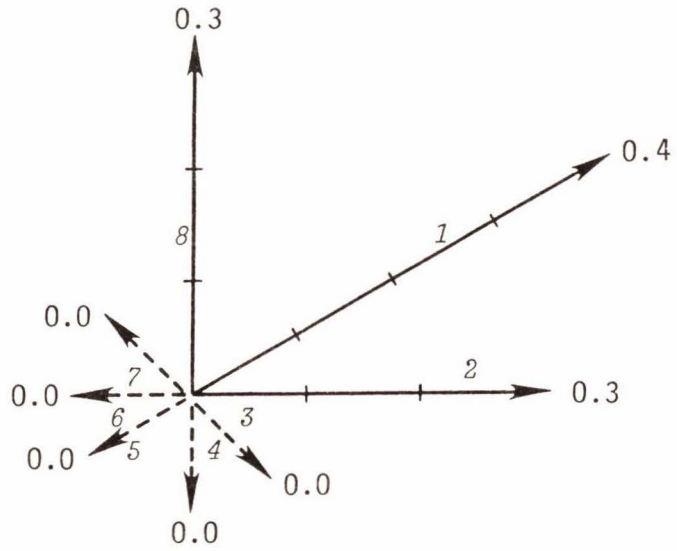

Figure 7. A wind/topography rosette with direction codes (italics) for the representative Level 1 unit.

Table 3. Partial neighbors matrix for representative Level 1 unit (Figure 6).

Stand	Neighbors/(orientation)								
1	2 (1)	2 (2)	9 (8)	10 (6)	10 (7)				
.			.						
.			.						
.			.						
12	2 (4)	8 (3)	8 (2)	9 (5)	11 (6)	15 (7)	16 (7)	17 (8)	18 (1)
.			.						
.			.						
.			.						
18	8 (3)	12 (4)	12 (5)	17 (6)	17 (7)	19 (8)	20 (1)	20 (2)	
19	17 (6)	17 (5)	18 (4)	20 (3)	20 (2)	21 (1)	21 (7)	21 (8)	
20	7 (4)	8 (5)	18 (6)	19 (7)	21 (8)				
21	17 (5)	19 (4)	20 (3)						

Table 4. Partial continuation matrix for representative Level 1 unit (Figure 6).

Direction of initial dispersal	Continuation dispersal direction(s)
1	1, 2, 8
2	1, 2
.	.
.	.
.	.
8	8

rosette, is to allow the user to control the degree to which beetles spread out as they move farther from the point of outbreak. Another reason for using the matrix is to "prevent" beetle units from moving back into the stand they originally dispersed from. The proportion of beetle units dispersing in each continuation direction will be determined by normalizing the appropriate proportions from the wind/topography rosette to a value of one.

For our example, beetles moved into stand 18 from direction 1; row 1 of the continuation matrix specifies that subsequent dispersal will occur in directions 1, 2, and 8. Row 18 of the neighbors matrix indicates this subsequent dispersal will be to stands 19 and 20. Since stands 19 and 20 are within the maximum dispersal distance for mountain pine beetles (Figure 5,m), dispersal calculations will be made for both. Two approaches were discussed for specifying the maximum dispersal distance parameter; first, having the user input a constant value or, second, using the dispersal distance calculation described earlier.

Movement (Figure 5,n) and absorption (Figure 5,o) of excess beetle units will be calculated as described earlier. From the wind/topography rosette, 40 percent (168) of the 420 excess beetle units in stand 18 will continue moving in direction 1 to stand 20. Assume that stand 20 has a relatively high hazard index and can therefore absorb 200 beetle units and that again, 10 percent of the immigrating beetle units will be lost to natural mortality. Under these circumstances, approximately 17 beetle units will "die" (168 x 0.1), approximately 151 will be absorbed (168 - 16.8), and there will be no excess beetle units moving in direction 1 to continue dispersing. The stand still has the capacity to absorb 49 units (200 - 151).

Similar calculations will next be made for beetle units dispersing in other directions from stand 18 (Figure 5,p). The rosette indicates that 30 percent of the 420 units from stand 18 will disperse in direction 2 and the neighbors matrix indicates these 126 units will also end up in stand 20. If 10 percent of the beetle units are again lost to mortality and 49 units are absorbed through infestation of green trees, then approximately 64 beetle units (126 - 12.6 - 49) will continue dispersing. For beetle units dispersing in direction 8 (to stand 19) from stand 18, assume that the calculations indicate 50 beetle units will continue dispersing from stand 19.

At this point, a second set of continuation dispersal calculations (Figure 5, m-p) will be made because there are still excess beetle units in stands 19 and 20 (Figure 5,q). The units in stand 19 entered the stand from direction 8 and the continuation matrix indicates they can only continue dispersing in direction 8. Therefore, all of the excess beetles will end up in stand 21.

The continued dispersal of beetles from stand 20 illustrates an unresolved problem with the contagion approach. The problem arises because of the order in which dispersal directions will be calculated. Excess beetle units that enter stand 20 from direction 1 will continue dispersing in directions 1, 2, and 8. Excess beetle units which enter from direction 2 will only continue in directions 1 and 2. If direction 1 is calculated first, all beetle units from

direction 1 will be absorbed while 64 units from direction 2 will continue movement in directions 1 and 2 (to stand 22). If direction 2 is calculated first, those 64 excess units would have come from direction 1 with continued movement in directions 1, 2, and 8 (to stands 21 and 22). Thus, the pattern of dispersal can be greatly influenced by a calculation sequence that is in large part arbitrary and completely independent of the behavior of mountain pine beetles. One possible solution is to proportionately absorb units entering the stand from all directions. In our example, separate calculations would then be made for continued dispersal of units entering stand 20 from direction 1 (continued dispersal in directions 1, 2, and 8) and continued dispersal of units entering stand 20 from direction 2 (continued dispersal in directions 1 and 2).

The absorption of excess beetles in stands 21 and 22 illustrates another unresolved issue. The calculation of absorption as discussed in the workshop will be based on the stand's hazard index and modified by a factor based on the stand's width or shape. However, a portion of both stands 21 and 22 is outside the maximum dispersal distance. This factor should probably be incorporated into the absorption calculations.

If excess beetle units remained in stands 21 or 22, a third iteration of the continued dispersal calculations would be started. However, since any subsequent dispersal would be outside the maximum dispersal distance (Figure 5,m), the excess beetle units would remain within the stands (Figure 5,r). The effect of these excess beetles on the stand was not discussed in detail; however, it was suggested that they would probably "die" since the stand cannot absorb any more beetle units.

At this point, all dispersal resulting from the initial movement from stand 12 in direction 1 would have been calculated. The entire process will be repeated for dispersal from stand 12 that starts in direction 2 and again for dispersal starting in direction 8 (Figure 5,s). When calculations for all dispersal directions from stand 12 have been completed, the mountain pine beetle model will be run for the next forest stand and the contagion model run if outbreak conditions are indicated (Figure 3). After mountain pine beetle damage, production, and contagion calculations have been made for all stands, the mountain pine beetle index will be calculated as described earlier.

FOREST STAND MODEL

The forest stand model was discussed only peripherally at the workshop. However, several conclusions were reached concerning the type of stand model needed to support the mountain pine beetle and contagion models.

Although PROGNOSIS (Wykoff et al. 1982) is the most widely used forest stand model in western Forest Service Regions, it is far more detailed a model than is required for IPIAS. Because of its complexity, PROGNOSIS has a feasible operational capacity of about 200 stands.

The Intermountain Forest and Range Experiment Station is planning a simplified version of PROGNOSIS that seems more suited for use in IPIAS. This version will be based on the growth relationships currently in PROGNOSIS but will not include the various extensions. The simpler version will basically produce a tree list as output and will use some data compression techniques so that classes of trees, rather than individuals, are tracked. This version might also provide options for aggregating similar, contiguous stands such that it could be used on Level 1 units with a very large number of stands. The sensitivity of the mountain pine beetle and contagion models to inputs from the stand model will have to be evaluated to determine the degree of data compression and stand aggregation that is tolerable.

SYSTEM CALIBRATION, VERIFICATION, AND REVIEW

CALIBRATION AND VERIFICATION NEEDS - As mentioned earlier, IPIAS will not predict which specific stands will be hit next during a particular outbreak; rather, it will indicate the types of stands (e.g., species/size composition, upslope versus downslope from existing outbreaks) most likely to be problems. Therefore, verification of IPIAS models will be based more on the ability of the models to predict relative differences between management prescriptions rather than absolute values for each. Also, because of the complexity of the models and limitations of historical data, it is possible that there is no way to verify the entire IPIAS system. For example, two adjacent stands may have had an outbreak triggered by weather at the same time; however, due to different stand characteristics they might have exhibited different rates of outbreak development (i.e., red-top trees at different times). It may be impossible to differentiate this situation from contagion effects given currently collected data and sketch maps and therefore, no way to evaluate model predictions under similar conditions. Because of these limitations, individual components of the various models and aggregations of these components will be verified to the extent possible with existing data. The verification process will continue in the future as additional information becomes available.

In order to have the information necessary to adequately calibrate and verify the various components of IPIAS, a number of activities should be initiated. First, there is a need to collect and digitize outbreak sketch maps for several areas. It might be useful to give preference to areas that also have stand maps for the corresponding time interval. Suggested areas include the north slope of the Uintas, the Targhee, the Gallatin, the Blue Mountains, the Deschutes Plateau, and Kintla Lake.

In addition to digitizing current outbreaks, control areas should be established for future detailed mapping. The mapping could be based on successive years of photo interpreted aerial photography and should indicate individual red-top trees (rather than clusters) so that the beginning of outbreaks can be seen. In addition to these maps, the stand data meteorological data, topographical data, etc., required by the mountain pine beetle and contagion models, should be collected.

The contagion modeling approach chosen for IPIAS will require some relatively small changes in the forest data base and the geographic information system. In order to initiate the simulation models, the forest stand data base will have to contain some information on the current status of mountain pine beetle infestation. The most useful information would be the number of red-top trees or clusters. In addition to stand level data, some information on infestation status of nearby Level 1 units may be needed in order for the models to properly generate "independent" outbreaks. Either the forest stand data base or the geographic information data base will have to contain, for each stand, a list of neighboring stands and either the orientation of those neighboring stands from the subject stand, or the centroids of all stands (from which orientation can be computed). The MOSS geographic information system can currently generate this information for only one stand at a time. Adding a batch capability to MOSS to generate these lists and orientations for all stands in the geographic data base would be very useful.

SYSTEM REVIEW - Review of IPIAS modeling approaches will be done initially by workshop participants. Periodic progress reviews will be performed by a peer group, including personnel from the USDA Forest Service, the CANUSA MPB program, and various academic institutions. In addition to evaluating progress on the mountain pine beetle and contagion models, the sessions will review work associated with the CANUSA mountain pine beetle program and evaluate its applicability to IPIAS.

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